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# PWM-based PPM Format for Dimming Control in Visible Light Communication System

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**Abstract**—We report simulation results of pulse width modulation (PWM)-based pulse position modulation (PPM) signal format for visible light communication systems. For simultaneous operation of data transmission and dimming control, PPM data format is added to PWM dimming control signal. To show dimming control, the PWM duty ratio is changed from 40 % to 80 % during PPM data transmission. The PWM frame rate is set to 1 kHz to avoid flickering in human eyes. The PPM data rate is set to 20 kb/s. The waveforms, eye diagrams and BER of this system are calculated. The simulation shows the BER of  $1 \times 10^{-5}$  is achievable.

## I. INTRODUCTION

Recently, many research results on indoor optical wireless communication using illumination LEDs have been reported [1-10]. Compared to conventional lighting methods such as fluorescent or incandescent light, LED lighting is very useful due to its advantages such as efficiency, low power consumption, environmental friendliness, eye safety, and no regulation for radiation. Therefore, the application of them draws much attention for display backlight unit (BLU), car lamps, indoor colorful illuminations, etc.

In addition, illumination LEDs are used not only as lighting devices, but also as optical sources for indoor optical wireless communication systems, the so-called visible light communication (VLC) systems. The VLC has several advantages that it is strong against eavesdropping because light cannot penetrate the opaque wall. And, the VLC wavelength range of 380 nm ~ 750 nm is not regulated. Therefore, we expect that VLC can provide high transmission speeds in indoor communication along with the development of LEDs with wide modulation bandwidth.

Recently, a combined system of Ethernet and VLC using DPPM modulation method is reported by Rufo et al. [2]. A predicted normalized power distribution and spatial distribution of Q factor using on-off keying non-return-to-zero (OOK-NRZ) modulation method are reported at 5 Mb/s data rate in indoor diffuse cellular visible light communication system by Wu et al. [3]. Grubor et al. shows results on illuminance distribution, SNR distribution, broadband broadcasting using white LEDs, which have blue LEDs and phosphorous layer [4]. Combining PWM based dimming is performed for VLC system based on DMT [5].

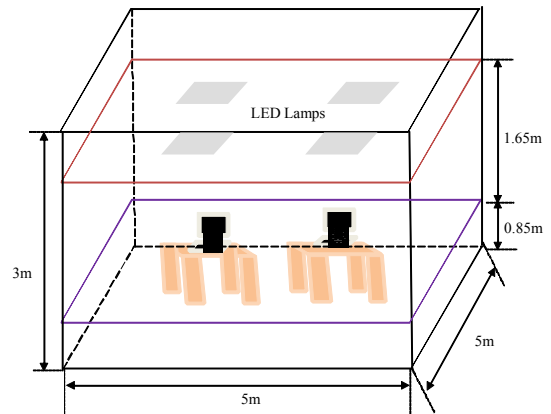


Figure 1. Indoor VLC simulation environment.

Since VLC system will act as illumination as well, the dimming control function is needed. Previously, a joint brightness control and data transmission for VLC systems by Siddique and Tahir [6] and a joint LED dimming method with high capacity VLC is proposed based on overlapping PPM (OPPM) [7] have been reported. Also, we have proposed a data stream of NRZ-OOK data stream over PWM dimming signal and demonstrated the operation of the system based on that signal format [8].

PPM is power efficient compared with NRZ since it avoids the DC and lower frequency components of the spectrum [2]. Also, it maintains the dimming contribution from its constant average power. PWM is an widely used method for brightness control [6]. Therefore, we suggest the PPM data signal based on PWM dimming control signal for VLC systems. We examine the performance of the system using a simulation program, developed using MATLAB and Simulink.

Previously, we reported an experimental results on PPM data stream over PWM dimming signal [10], where the PPM data rate was set to 1 kbits/sec whereas the PWM frame rate is set to 1 kHz. A simulation program is developed and the simulation results are reported on eye diagram and BER curve.

This paper organized as follows. In Section II, the optical channel is described. In Section III, the signal format is explained in detail.

In Section IV, the simulation results are shown. The illumination distribution and received optical power distribution on the desktop surface are calculated. Then, the signal waveforms including the recovered PPM data signal, eye diagrams and BER curve are shown. Finally, we concluded the paper with Section V.

## II. OPTICAL CHANNEL

The room model in Fig.1 has the size of 5 m x 5 m x 3 m. Four LED transmitters are installed above 2.5 m from the floor. Each LED transmitter is assumed to be composed of 3600 LEDs, whose center luminous intensity is 0.63 cd. And, the receiver is installed on the desk and the height of the desk is 0.85 m. The reflection at each wall is assumed to be Lambertian. The first-order reflections are considered for simulation. The illumination represents the brightness of an illuminated desktop surface. The luminous intensity at an angle  $\phi$  is given by:

$$I(\phi) = I(0)\cos^m(\phi), \quad (1)$$

where  $I(0)$  is the luminous intensity of the white LEDs,  $\phi$  is the angle of irradiance, it is assumed that LED lighting has a lambertian radiation pattern [9],  $m$  is the order of lambertian emission and is given by the semi-angle at half illumination of the LED  $\phi_{1/2}$  as:

$$m = -\ln 2 / \ln(\cos \phi_{1/2}), \quad (2)$$

A horizontal illumination  $E_{hor}$  at a point (x, y, z) on the desktop surface is given by:

$$E_{hor} = \frac{I(0)\cos^m(\phi)}{D_d^2 \cos(\psi)}, \quad (3)$$

where  $D_d$  is the distance between transmitter and receiver,  $\psi$  is the angle of incidence.

For assessing communication performance with the proposed signal format, the received optical power is calculated by the channel DC gains  $H_d(0)$ , on directed paths and  $H_{ref}(0)$ , on reflected paths with the Eq. (4) [9].

$$P_r = \sum^{LEDs} \{P_t H_d(0) + \int_{wall} P_t dH_{ref}(0)\}, \quad (4)$$

where  $P_t$  is the transmitted power from an LED and  $P_r$  is the received optical power at a receiver point. The channel DC gain is given [9] as:

$$H_d(0) = \begin{cases} \frac{(m+1)A}{2\pi D_d^2} \cos^m(\phi) \mathcal{T}_s(\psi) g(\psi) \cos(\psi), & 0 \leq \psi \leq \psi_c, \\ 0, & \psi > \psi_c \end{cases} \quad (5)$$

where  $A$  is the physical area of the detector in a PD,  $\mathcal{T}_s(\psi)$  is the gain of an optical filter, and  $g(\psi)$  is the gain of an optical concentrator.  $\psi_c$  denotes the width of the field of vision at a receiver.

TABLE I. SIMULATION PARAMETERS

Semi-angle at half power	60 [deg.]
Center luminous intensity	0.63 [cd]
Number of LEDs	3600 (60x60)
Transmitted optical power	169 [mW]
FOV at a receiver	60 [deg.]
Reflection coefficient of each wall	0.7
Gain of an optical filter	1.0
Refractive index of a lens at a PD	1.5
Detector physical area of a PD	1.0 [cm <sup>2</sup> ]

The optical concentrator  $g(\psi)$  can be given [9] as:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_c}, & 0 \leq \psi \leq \psi_c, \\ 0, & \psi > \psi_c \end{cases} \quad (6)$$

where  $n$  denotes the refractive index. The channel DC gain on the first reflection is given [9] as

$$dH_{ref}(0) = \begin{cases} \frac{(m+1)A}{2\pi^2 D_1^2 D_2^2} \rho dA_{wall} \cos^m(\phi) \cos(\alpha) \cos(\beta) \mathcal{T}_s(\psi) g(\psi) \cos(\psi), & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c \end{cases} \quad (7)$$

where  $D_1$  is the distance between an LED chip and a reflective point,  $D_2$  is the distance between a reflective point and a receiver,  $\rho$  is the reflectance factor,  $dA_{wall}$  is a reflective area of small region,  $\alpha$  is the angle of irradiance to a reflective point,  $\beta$  is the angle of irradiance to the receiver.

The values of physical parameters such as semi-angle at half power, center luminous intensity and transmitted optical power, etc. are listed in Table I. The parameters for LED is quoted from a commercial LED [11].

The optical waveforms, eye diagrams and bit error ratio (BER) will be calculated using the proposed signal format based on PPM data stream over PWM dimming signal. We assumed that the indoor VLC channel is an additive white Gaussian noise (AWGN) channel.

## III. SIGNAL FORMAT

The proposed signal format is shown in Fig. 2. The PWM signal is for dimming control. The width of a PWM pulse is proportional to the dimming level of illumination. The PPM modulated data signal is transmitted with the

PWM dimming control signal, regardless of the ON state during a PWM period. To show signal shapes during dimming control, we show the instant at the dimming level change from 80 % to 40 %.

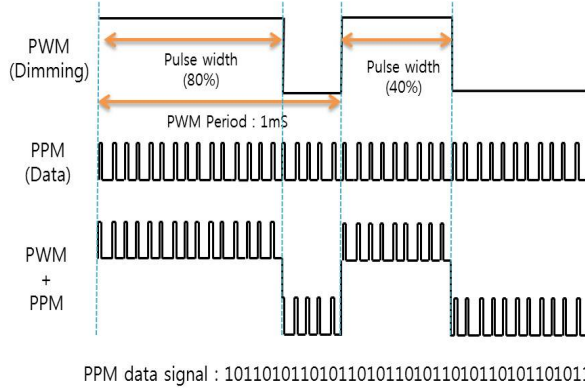


Figure 2. PPM-PWM signal format.

The binary PPM data pulses occupy 10 % of the PWM dimming period. The PPM pulse width is 5  $\mu$ s within a slot period of 50  $\mu$ s. Therefore, the guard time is set to 40  $\mu$ s.

#### IV. SIMULATION RESULTS

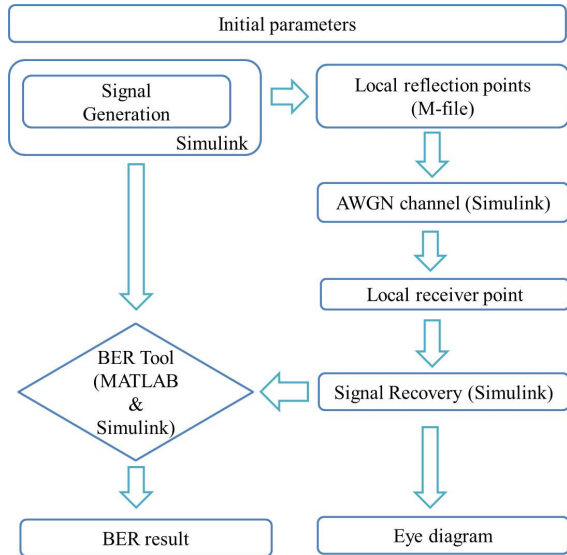


Figure 3. Flow chart of simulation.

Fig. 3 shows the block diagram which explains the simulation process. The PWM pulses for dimming and PPM pulses for data signal are generated at Simulink blocks. The combined signal for the proposed signal format modulates LEDs and the modulated light signal

experiences reflections at each wall. The effect of reflections is implemented in MATLAB m-files and AWGN is added using Simulink. The recorded data are used for calculation of illumination, received optical power distributions and waveforms.

##### A. Illumination Distribution

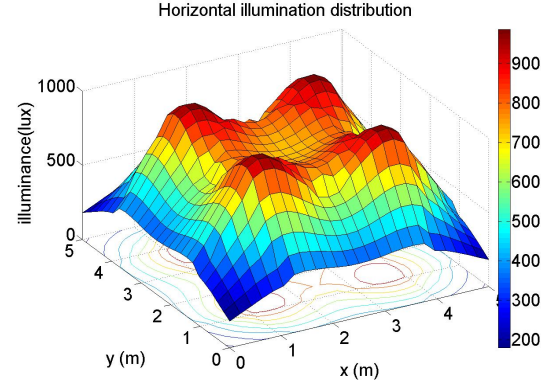


Figure 4. Illumination distribution on the desktop surface. (Max : 986.45 lx, Ave : 625.40 lx, Min : 180.58 lx).

Fig. 4 shows the illumination distribution on the desktop surface using Eq. (3). Except corners, the average illuminance level is 625.40 lux and it meets the ISO recommendation for office work.

##### B. Optical Power Distribution

Fig. 5 shows a optical power distribution on the desktop surface using Eq. (4). We assume LEDs with RGB three-chip in a package [11].

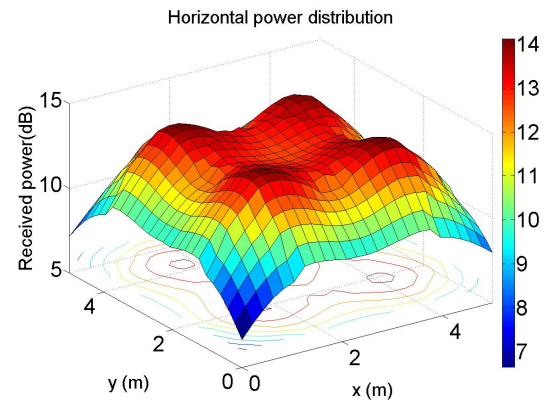


Figure 5. Optical power distribution on the desktop surface. (Max : 14.12 dB, Average : 11.85 dB, Min : 6.65 dB).

### C. Signal Waveforms

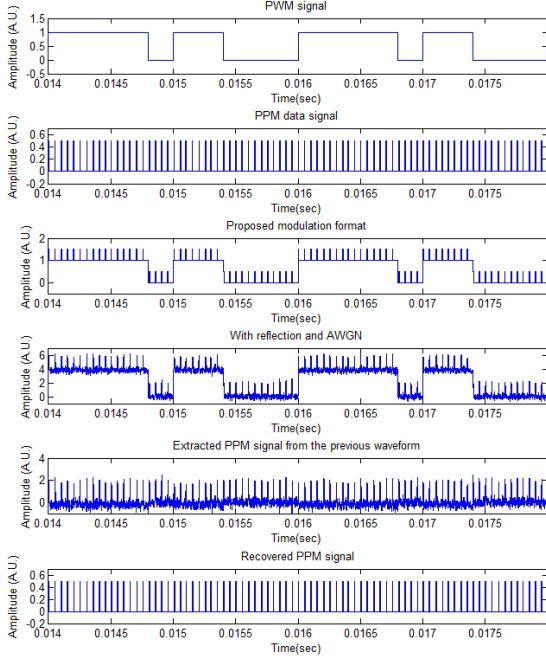


Figure 6. Waveforms of PPM data stream over PWM signal..

In this simulation, we assume that PWM duty ratio is set to change between 80 % and 40 % for brightness and the PWM frame rate, which ensures no flickering at the dimming rate over 500 Hz. The PPM data rate is set to 20 kbits/sec.

Fig. 6 shows the calculated signal waveforms along with flow chart in Fig. 3. The PWM and PPM signals are added in synchronism and the proposed signal waveform is shown on the third figure. Then, the reflection and AWGN is added and the recovered PPM signal is shown.

### D. Eye diagrams

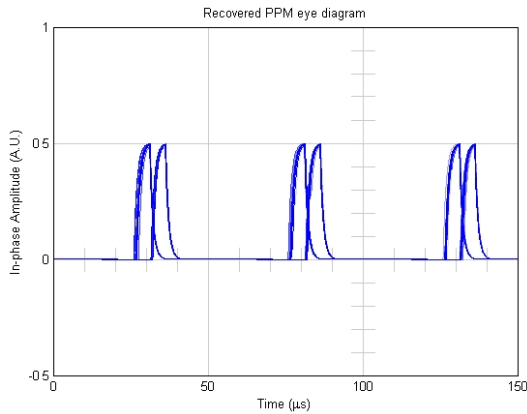


Figure 7. Eye diagram of the recovered PPM signal.

Fig. 7 shows the eye diagram of the PPM signal extracted from the waveform in Fig. 6. As explained in Section III, it is shown that the slot time of PPM is 5  $\mu$ s. Therefore, Fig. 7 shows that the slot time of 2-ppm is 10  $\mu$ s and the guard time is 40  $\mu$ s.

### E. Bit error ratio (BER)

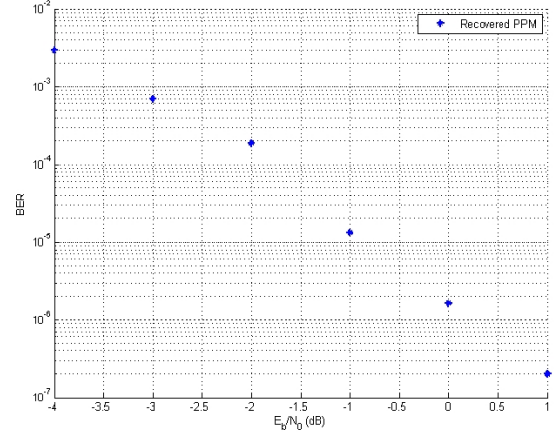


Figure 8. Bit error ratio.

Fig. 8 shows the BER of this system. We find that the BER value of about  $1 \times 10^{-5}$  is obtained when  $E_b/N_0$  is larger than -1 dB.

### V. CONCLUSION

We have shown a simulation result on a VLC system which transmits PPM data stream with PWM dimming control signal. We calculated the optical power distribution on the desktop surface assuming white LEDs. We proposed a PPM data signal for data transmission based on the PWM dimming control signal. The PWM duty ratio was set to change between 40 % and 80 % for brightness control and the PWM frame rate 1 kHz. The PPM data rate was set to 20 kHz. We have shown the calculated waveforms, eye diagrams and BER curve. The BER of  $1 \times 10^{-5}$  has been obtained.

### ACKNOWLEDGMENT

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